Operational Performance of the Horizontal Fast Rise EMP Pulser at the Patuxent River EMP Test Facility

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Abstract

For the past two years, the Naval EMP test facility located at the Patuxent River Naval Air station has been working with L-3 Pulse Sciences to develop and procure the new PS-6 pulser developed under the Horizontal Fast Rise EMP (HFREMP) project. The PS-6 pulser was designed to compliment and upgrade the Horizontally Polarized Dipole (HPD) simulator and will greatly improve its test capabilities for future EMP testing. The new PS-6 pulser utilizes two battery charged, dual opposing Marx generators (+/- 3 MV) with two pulse compression circuits per Marx, to generate an EMP pulse with a peak amplitude of up to 77 kV/m at a distance of 24.5m away from the source. Combined with the two dual compression circuits, a 200 PSIG center switch allows the PS-6 pulser to generate a fast rise time of 1.3 ns to 2.8 ns. By utilizing the multiple onboard diagnostics and free field measurements, the operators are able to adjust various switch timing parameters/settings to achieve a multitude of peak amplitudes, rise times, and Full Width Half Maximum (FWHM) values required for EMP testing. In this paper, we will examine a few of the operational parameters and the resulting performance, demonstrating the versatility and capability of the new PS-6 pulser.

I. INTRODUCTION

The EMP test facility located at the Naval Air Station Patuxent River, MD was commissioned in 1986 under the Take Charge and Move Out (TACAMO) program. The facility utilized the hybrid elliptical horizontally polarized dipole antenna that was driven by the Maxwell Labs 5 MV (ML-5) dual opposing Marx generator pulser as shown in Figure 1. The entire system (125 m long) is located outdoors and is constantly exposed to coastal wind, humid summers, and below freezing winters. The ML5 operated with several high voltage and equipment reliability issues that continued to be a maintenance concern due to original design constraints and lifetime deterioration issues. The ML5 design is late 1970 to early 1980 technology that included high voltage trigger generators designed to operate in an indoor, laboratory-controlled environment. The ML-5 pulser was originally designed to generate the Bell Labs EMP waveform and was modified to incorporate a variable gap output switch and additional peaking capacitors to provide a variable output and faster rise time as the EMP test environment requirements were updated over time. The Defense Threat Reduction Agency (DTRA) reviewed the performance of the Horizontally Polarized Dipole Simulator (HPD) in 2004 and determined that overdriving test objects by up to 20% was required to produce a good representation of the EMP E1 environment. With the combination of original design limitations and environmental deterioration issues, and the assessment completed by DTRA, the Horizontal Fast Rise EMP (HFREMP) project was developed to remedy these major shortfalls.

The HFREMP project replaced the ML-5 pulser source with a new, environmentally sealed pulser utilizing new/updated technology to greatly improve the reliability, readiness, and overall test capabilities of the EMP test facility.

Figure 1: Horizontally Polarized Dipole EMP simulator previously utilizing the ML-5 pulser source.

The HFREMP project began in October of 2007, and a contract was awarded to L-3 Communications, Pulse Sciences in the fall of 2008. L-3 Pulse Sciences then began to design, construct, and test the new 6 MV pulser to drive the horizontally polarized EMP simulator[1]. Once the preliminary operational checkout was completed, the

978-1-4577-0631-8/11/$26.00 ©2011 IEEE

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2011	**N/A**	-

4. TITLE AND SUBTITLE	
Operational Performance of the Horizontal Fast Rise EMP Pulser at the Patuxent River EMP Test Facility	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Air Systems Command Patuxent River, MD 20670**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.

14. ABSTRACT

For the past two years, the Naval EMP test facility located at the Patuxent River Naval Air station has been working with L-3 Pulse Sciences to develop and procure the new PS-6 pulser developed under the Horizontal Fast Rise EMP (HFREMP) project. The PS-6 pulser was designed to compliment and upgrade the Horizontally Polarized Dipole (HPD) simulator and will greatly improve its test capabilities for future EMP testing. The new PS-6 pulser utilizes two battery charged, dual opposing Marx generators (+/- 3 MV) with two pulse compression circuits per Marx, to generate an EMP pulse with a peak amplitude of up to 77 kV/m at a distance of 24.5m away from the source. Combined with the two dual compression circuits, a 200 PSIG center switch allows the PS-6 pulser to generate a fast rise time of 1.3 ns to 2.8 ns. By utilizing the multiple onboard diagnostics and free field measurements, the operators are able to adjust various switch timing parameters/settings to achieve a multitude of peak amplitudes, rise times, and Full Width Half Maximum (FWHM) values required for EMP testing. In this paper, we will examine a few of the operational parameters and the resulting performance, demonstrating the versatility and capability of the new PS-6 pulser.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

new pulser was delivered to Patuxent River October 1st, 2010, where it was re-assembled, installed, and tested in the HPD antenna by December 1st.

Over the next four months, the pulser was rigorously tested and its capabilities examined, revealing a pulser source with great potential, having multiple operational configurations and vast flexibility in electromagnetic field output. To follow the naming nomenclature of the previous pulser source new horizontally polarized EMP simulator pulser has been officially titled the Pulse Sciences 6 MV (PS-6) pulser.

II. PULSER DESIGN

The PS-6 pulser utilizes two dual opposing Marx generators with two pulse compression stages per Marx to deliver a fast rise double exponential Electromagnetic Pulse which radiates from its 150 Ohm biconical launch antenna[1]. A simplistic equivalent circuit model is shown in Figure 2.

Each Marx Generator utilizes 30 stages, with an erected capacitance of 1.33 nF per Marx, which is designed for a variable voltage output range of 750 kV to 3 MV. By utilizing opposite Marx polarities, the differential voltage output range is 1.5 MV to 6 MV. Due to a flashover event when operating at 5.2 MV during preliminary testing, the Marx Generators have been limited to a nominal operating voltage of 2.4 MV per Marx until future testing can be completed. Once the Marx Generator is triggered, it erects and then charges the 610 pF first stage peaking capacitor in a nominal time of about 75 ns.

A triple electrode spark gap (triple switch) designed to hold off a maximum voltage of 3 MV isolates the first stage peaking capacitor from the second stage peaking capacitor until full charge is reached. By utilizing various gases and pressures, the triple switch breakdown voltage can be varied as well. Once the triple switch closes, the final 168 pF second stage peaking capacitor then begins to charge at a faster rate than the first stage peaking capacitor (< 25 ns). The final switch (output switch) isolates the two second stage peaking capacitors from one another until the desired breakdown/output voltage is reached and then closes with a rise time around 1.5 ns - 2 ns.

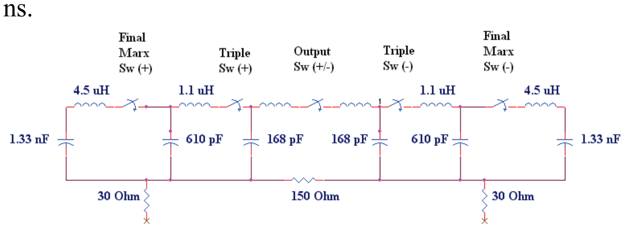

Figure 2: Simplistic PS-6 pulser equivalent circuit model.

The output switch is a 200 PSIG SF_6 insulated spark gap with a remote controlled movable electrode to vary the gap distance, thus controlling the breakdown voltage. The output switch is designed to hold off the full differential voltage of 6 MV. The nominal peaking capacitor charge times stated above were varied, often using shorter times to produce various simulator output waveforms, as described below.

After the PS-6 pulser was delivered to Patuxent River and re-assembled, operational characterization began with the checkout of the basic system functions. One of the design criterion placed upon the design of the pulser was to have the ability to prevent undesired electrical stresses in the event of a single side pre-fire. If a Marx generator discharges before being triggered then the energy transfer will begin and will reach the second peaking capacitor. Since the full differential voltage is not applied across the center switch, it will most likely not close, leaving a long charge upon the second peaking capacitors, possibly risking capacitor flashover and damaging the unit.

To prevent this, a 30 ohm clamping arm is connected to the end of the Marx generator in parallel with the first peaking capacitor during the charging phase. The clamps are then quickly removed before triggering both sides, and are shown as a no connect (open) in the circuit model in Figure 2. The 30 ohm load allows a damped discharge of the Marx to occur without stress charging the peaking capacitors.

III. PULSER OPERATION

Another use for the clamping arms is to verify the side to side synchronicity before attempting to breakdown the output switch. This is a key performance requirement since the timing must be exact (within 8 ns or less) in order to achieve efficient EM field generation. To accomplish this, the triple switches on both sides are brought up to high pressure to prevent closing and then the Marx generators are deliberately discharged into the clamping arms. Figure 3 below shows a typical clamp shot, comparing the timing between the two sides.

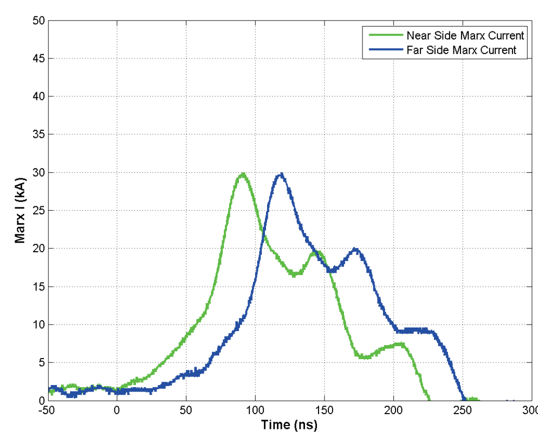

Figure 3: Near and far side Marx current timing comparison showing 23.56 ns of separation contributed to the fiber optic length delay.

A. Single Ended Operation

Another feature designed into the pulser is the ability to operate in single sided mode or only charging and discharging one of the two Marx generators through the center switch. Single sided operation can be performed by enabling either the positive or negative side of the pulser only, reducing the center switch gap breakdown to a range within a single Marx output, setting all switch pressures to normal operation except for the opposite Marx switch pressures, which are doubled to prevent closing , and operate with the clamps down. This is a beneficial capability that allows continued operation in the event of a single side default or failure. A single sided radiated EM field measurement is shown in Figure 4 and an equivalent circuit model is shown in Figure 5. Ideally, the opposite side clamp arm would be a direct short and the same side clamp would be open, thus allowing efficient energy transfer from the single Marx and broadening the FWHM of the pulse. Future capability of this mode of operation is expected to be analyzed further in the future.

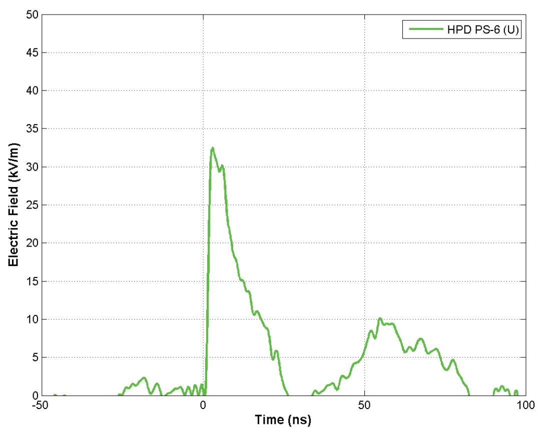

Figure 4: Single sided operation radiated electric field at 24.5 m away from the source.

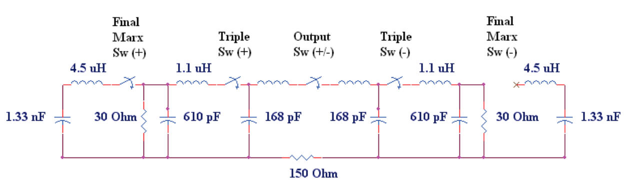

Figure 5: Simplistic single sided pulser operation equivalent circuit model.

B. Double Ended Operation

Once verification of the side to side timing is correct with minimal jitter, then the pulser can be operated in double ended mode. Double ended operation is typically used for generating high EM field levels that a single Marx cannot achieve. The lowest EM field output amplitude is 15 kV/m at a distance of 24.5 m from the source. This field level is achieved with the Marx generators set at a |750kV| output (1.5 MV differential output) and a stage voltage of 25 kV per stage. Attempting to operate below the 25 kV stage charge voltage results in instability in the Marx and introduces large amounts of jitter in the side to side timing relationship. Ideally, the double ended operations take place at a Marx generator output of |1 MV| (2 MV differential) or higher to achieved accurate repeatability of the pulse shape. For lower field levels, the single ended mode operation is utilized as previously mentioned.

Before utilizing the simulator for a test, the pulser must be "tuned in" to the desired pulse shape requested by the customer. With a second pulse compression stage, the PS-6 acts like a tunable Pulse Forming Network, with adjustments completed by varying the switch timing of the peaking circuits. Peaking circuits are used to achieve fast rise times from Marx generator based systems and the switching of the peaking capacitor to the load is critical [2]. A basic peaking circuit model is shown in Figure 6.

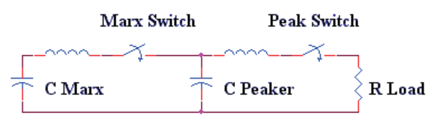

Figure 6: Circuital model of a basic peaking circuit

To efficiently transfer energy from the Marx generator/peaking circuit to the load, the peaking switch is closed when the peaking capacitor approaches the same voltage as the output of the Marx or when the Marx discharge current begins to roll off. If the output switch timing is late, then the Marx current will begin to fall off, the peaking capacitor will fully discharge, the inductance of the Marx will cause the remaining energy to lag, and cause a notch in the pulse shape. If the timing is early, then the peaking capacitor will not be fully charged, the peak voltage amplitude will not be immediately transferred to the load and the rising edge will "roll over".

Since the PS-6 utilizes two peaking circuits, great care must be taken with the switch timing of each peaking circuit stage. The most basic timing is having all the peaking switches close near the peak voltage. For example, the Marx generators are set to deliver an output voltage of |2 MV| to the first stage peaking capacitor, and the triple switch is set to close at |2 MV| to charge the second peaking capacitor. When the voltage on the second peaking capacitor reaches |2 MV|, the output switch has a differential voltage of 4 MV and closes, generating a double exponential EM pulse as shown in Figure 7, designated as EMP 1.

If the Marx generators and the triple switch are still set for |2 MV| but the output switch is reduced to close at a differential voltage of < 500 kV, then the second stage peaking capacitors discharge early and the rise time is reduced to the rate of discharge of the first peaking

capacitors. The EM pulse EMP 2 in Figure 7 shows this phenomenon at the 25 kV/m level on the rising edge. It should also be noted that the FWHM of the pulse was greatly increased by this "early switch-out" technique. These effects limit the energy in the high frequency content but increase the energy in the lower frequency content in comparison the EMP 1, as shown in Figure 8. By reducing the output switch closing voltage further, the second peaking circuit can be completely shorted out and give an EM pulse with a much slower rate of change, reducing the high frequency content even further.

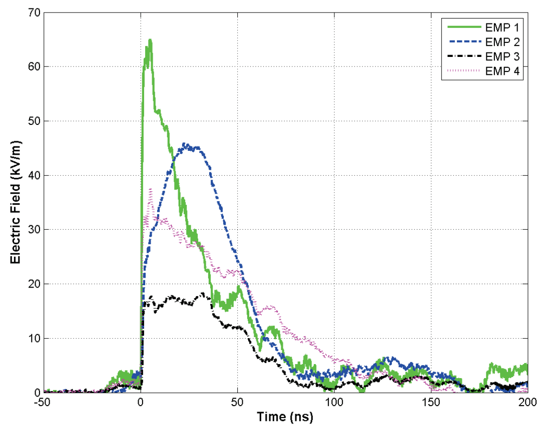

Figure 7: Various measured EM pulse shapes generated by the PS-6 pulser with various switch timing parameters.

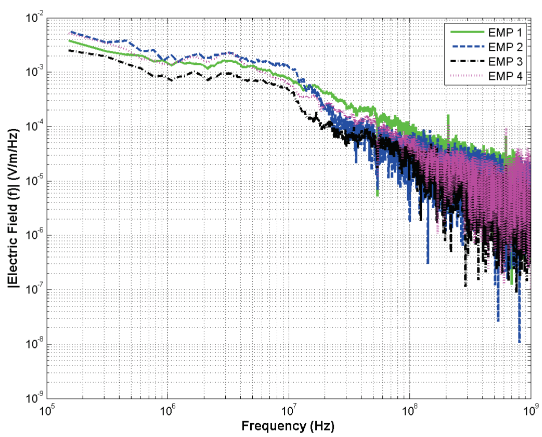

Figure 8: Various measured EM pulse frequencies generated by the PS-6 pulser with various switch timing parameters.

For the EM pulse EMP 3, the Marx generator output voltage was reduced to |1.2 MV|, the triple switch was set to close at |1.1 MV|, and the output switch was set to close at a differential voltage of 700 kV. The EMP 3 pulse shape illustrates the reduction in pulse amplitude as the entire system voltage is reduced, as expected, and that a "flat top" can be established with proper tuning of the early switch-out technique.

The last pulse shape, EMP 4, illustrates the effect of an evenly matched early switch-out technique where the Marx generator output voltage was set at |1.875 MV|, the triple switch closing voltage was set to |1.25 MV|, and the output switch closing voltage was set to a differential voltage of 1.25 MV. This is considered an evenly matched early switch-out technique since the differential voltage (side to side voltage) of the machine throughout the stages is evenly reduced by a third. Table 1 below illustrates this relationship of each of the previously discussed EM pulse shapes EMP 1 – 4.

Table 1.

	Diff. Marx Output V	Diff. Triple Switch V	Diff. Output Switch V
EMP 1	4 MV	4 MV	4 MV
EMP 2	4 MV	4 MV	500 kV
EMP 3	2.4 MV	2.2 MV	700 kV
EMP 4	3.75 MV	2.5 MV	1.25 MV

IV. SUMMARY

Over the past two years, the Naval EMP test facility located at Patuxent River Naval Air Station has been working with L-3 Communications Pulse Sciences division to develop, construct, and commission the Pulse Sciences 6 MV pulser. The PS-6 has shown a capability of generating specifically tailored EM pulse shapes with peak amplitudes ranging from below 15 kV/m in single ended operation, up to 77 kV/m in double ended operation. Overall, the PS-6 pulser utilizes advanced pulsed power methodologies and technology allowing greater operational flexibility, reliability, and efficiency over the previous ML-5 pulser. The PS-6 pulser is and will be great asset for the Patuxent River Naval Air Station EMP test facility for many years to come.

V. REFERENCES

[1] Bailey, V.; Carboni, V.; Eichenberger, C.; Naff, T.; Smith, I.; Warren, T.; Whitney, B.; Giri, D.; Belt, D.; Brown, D.; Mazuc, A.; Seale, T.; "A 6-MV Pulser to Drive Horizontally Polarized EMP Simulators," *Plasma Science, IEEE Transactions on* , vol.38, no.10, pp.2554-2558, Oct. 2010

[2] Adler, Richard J.;Smith, I.D.; Noggle, R.C.; Kiuttu, G.F.; "Pulse Power Formulary", North Star Research Corp., March 2001.

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